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Procedia Materials Science 3 (2014) 307 – 312

Procedia Materials Science

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20th European Conference on Fracture (ECF20)

The influence of weld joints on the failure mechanism of scaled double hull structures under collision load in finite element simulations

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Abstract

As a result of growing safety-related requirements in shipbuilding the design of double hulls in respect to accidents and collisions is mainly orientated on damage stability calculations. In order to increase the collision resistance and thereby the damage stability of ships the concept of an alternative stiffening system (English: plates strengthened stiffeners, German: Plattenverstärkte Profilsteifen – PVPS) invented by Röhr et al. (2008) was investigated for practical use within the scope of the project SideColl, funded by the German Federal Ministry of Economics and Technology (BMWi). A collision experiment with a scaled double hull structure is performed with the alternative stiffening system. Beside the experimental investigations numerical simulations with the finite element software LS-Dyna are conducted. With the adaption of suitable discretizations and fracture criteria in the finite element model the structural response in terms of the force-displacement curve are well predicted. Furthermore, the crack initiation and the failure mechanism are captured in good agreement with the experiment. An equivalent model for weld joints is applied to the double hull structure to reproduce the different material behavior at plastic deformations and fracture in the numerical analysis.

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: collision experiment; numerical simulation; fracture criterion; weld joints; plates strengthened stiffeners

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2211-8128
Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering
doi:10.1016/j.mspro.2014.06.053

1. Introduction

Ship accidents due to grounding or collision led in the past to danger of human life and to environmental pollution because of oil or cargo leakage. Such accidents occur as a consequence of human failure as well as of technical failure in coastal and frequently used waters. Therefore, it is crucial to adopt measures such as the improvement of the crashworthiness to ensure the structural integrity of the ship.

To predict the location of crack initiation and the failure mechanism of a double hull structure in numerical analysis of collision or grounding scenarios is still challenging and related with uncertainties. A variety of large-scale experiments are performed to validate finite element models for collision and grounding analysis.

Amdahl and Kavlie (1992) investigated the failure mechanism at grounding based on quasi-static large-scale experiments. Törnqvist (2003) defined the RTCL fracture criterion for numerical analysis of grounding and collision and verified the criterion with experiments of Amdahl and Kavlie (1992). He calibrated the fracture criterion on the material of the double hull structures and investigated the influence of the element length on the numerical fracture strain based on numerical analysis of tensile tests. Finite element simulations of the experiments with scaled double hull structures using the RTCL fracture criterion reveal that the criterion is capable to reproduce the force-displacement curves.

Karlsson et al. (2009) validate finite element models with large-scale specimens of double hull structures in quasi-static experiments. They used the shear fracture criterion to predict the crack initiation and propagation in the structure. The calibration of the fracture criterion was performed with large-scale experiments of unstiffened shell plates.

Alsos and Amdahl (2009) investigate the failure mechanism of grounding accidents by performing large-scale experiments with stiffened and unstiffened shell plates. Alsos et al. (2009) investigated these experiments numerically and compared results of finite element simulations using the RTCL (named after Rice, Tracey, Cockroft and Latham) and the BWH fracture criterion. Alsos et al. (2009) define the BWH criterion, which is a combination of the criterion of Bressan and Williams (1983) with the criterion of Hill (1952), and formulate the criterion as a limiting value of the major principal stress. Both criteria are initially defined as forming limit curves (FLC). FLC are used to predict instability in metallic materials. They describe a function of the major principal plastic strain and depend on the ratio of the strain rate. The numerical analysis with the RTCL and the BWH criterion are capable of reproducing the force-displacement curves of the experiments.

An alternative stiffening system (English: plates strengthened stiffeners, German: Plattenverstärkte Profilsteifen – PVPS) is experimentally and numerically investigated in the project SideColl to improve the crashworthiness. One collision experiment with alternative stiffening system and the approach of the validation will be presented in this paper. The finite element simulations are performed with the RTCL fracture criterion and the calibration as well as the adjustment on to the element length of the criterion is carried out in the same way as by Alsos et al. (2009). The varying material and fracture behavior of the weld metal compared to the base metal had an influence on the failure mechanism in the experiment. Different than in other numerical investigations of grounding and collision experiments it is necessary to consider weld joints for the validation of the finite element model.

2. Experimental setup and large-scale specimen

The experimental setup of the collision experiment is representing the striking ship as a bulbous bow and penetrates the double hull structure perpendicularly (Fig. 1). Due to technical reasons the collision test plant is laid out symmetrically and therefore the bulbous bow is designed as a rotationally symmetric body with high stiffness compared to the double hull structure. The experiment was performed quasi-static with a load velocity of 2 mm/s. The collision test plant was developed by the Hamburg University of Technology (TUHH) and the experiment was conducted in collaboration with the University of Rostock.

The large-scale specimen consists of a support-construction, which is passing the occurring reaction forces during the experiment on to the collision test plant (Fig. 1b). The support-construction is made out of shipbuilding steel grade A36 and has a plate thickness of 20 mm. The support-construction is surrounding the actual double hull structure, which is manufactured from shipbuilding steel grade A. The double hull structure is composed of web

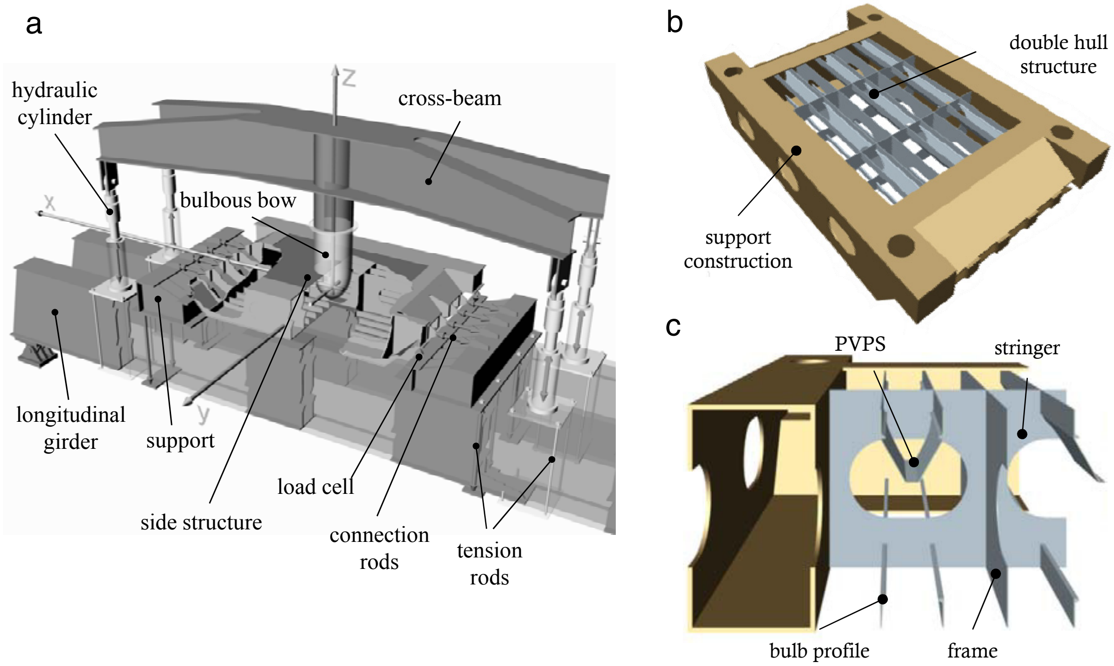

Fig. 1. (a) Collision test plant of TUHH (see Schöttelndreyer et al. (2013)); (b) Large-scale specimen including support construction and double hull structure; (c) Cross section of a quarter model of the large-scale specimen.

frames and stringers with a thickness of 5 mm, the bulb profiles (HP 120x6), the PVPS (4 mm) and the outer and inner shell (4 mm) (Fig. 1c). The large-scale specimen is 5.4 m in length, 3.5 m in width and 0.95 m in height. It was derived from a double hull design of an anchor handling tug supply vessel of the German shipyard P+S-Werften.

3. Experimental results

Beside the observed failure mechanism of the double hull structure the force-displacement curve is a crucial experimental result. The failure mechanism can be characterized by a few points in the force-displacement curve. The outer shell fails at a displacement of the bulbous bow of 100 mm and a reaction force of 700 kN (1 in Fig. 2). A crack appears next to the weld joint of one bulb profile and grows parallel to the profile with increasing displacement. Due to manufacturing reasons gaps of a few Millimeters width between PVPS and stringer exists. The crack paths go through both profiles next to the stringer and lead to these gaps. As a result of the failing bulb profiles the reaction force declines from the maximum of 1575 kN to approximately 350 kN (2 in Fig. 2). At a displacement of 870 mm and 970 mm the bulb profiles of the outer shell fail a second time where the cracks also go through the profiles next to the other stringer (2’ in Fig. 2). The PVPS as well as parts of the profiles and the outer shell are separated from the remaining structure. The inner shell fails at a reaction force of 1020 kN and a displacement of 1390 mm (3 in Fig. 2).

4. Determination of true stress-strain relations and calibration of the RTCL fracture criterion

The Young’s modulus and the true stress-strain relations of the different steel batches and the weld metal of the large-scale specimen are determined by tensile tests. Until necking of the tensile specimen true stress-strain relations can be obtained from technical stress-strain relations analytically. To describe the true stress-strain relation after onset of necking the weighted average method of Ling (1996) is used. A weighted, averaged curve from a linear equation with the slope at onset of necking and the power law ($\sigma = K\varepsilon^n$) is established. The weight constant is

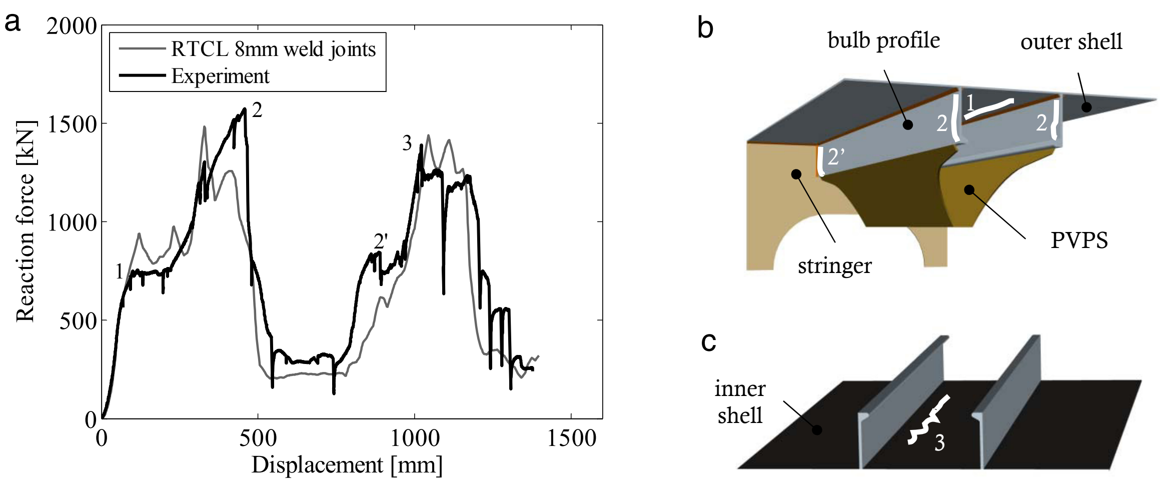

Fig. 2. (a) Force-displacement curve of the collision experiment and finite element simulation; (b) schematic illustration of the crack paths in outer shell, bulb profiles and PVPS; (c) schematic illustration of the crack paths in inner shell.

obtained from finite element analysis of the tensile tests with varying discretizations. A detailed description of the determination of the true stress-strain relations is given in Schöttelndreyer et al. (2013).

The RTCL fracture criterion is defined by Törnqvist (2003) and is composed of the criterion of Rice and Tracey (Fischer et al. (1995), Hancock and Mackenzie (1976)) and the criterion of Cockroft and Latham (1972). A damage indicator D is calculated by the integration of a function dependent on the stress triaxiality over the plastic strain. Furthermore, the indicator is normalized by the fracture strain at uniaxial tension (critical strain ε_0).

$$D = \frac{1}{\varepsilon_0} \int f(T)_{RTCL}\, d\varepsilon \tag{1}$$

Failure occurs if the damage indicator reaches unity. The integrand $f(T)_{RTCL}$ in equation (1) is determined by:

$$f(T)_{RTCL} = \begin{cases} 0 & for \quad T \le -\frac{1}{3} \\ 2\dfrac{1+T\sqrt{12-27(T)^2}}{3T+\sqrt{12-27(T)^2}} & for \quad -\frac{1}{3} < T < \frac{1}{3} \\ \dfrac{1}{1,65}\exp\left(\dfrac{3}{2}T\right) & for \quad T \ge \frac{1}{3} \end{cases} \tag{2}$$

For stress triaxialities less or equal than -1/3 no failure is considered in the RTCL criterion and $f(T)_{RTCL} = 0$. For stress triaxialities in the range of -1/3 to 1/3 the fracture criterion of Cockroft and Latham and for stress triaxialities greater than 1/3 the criterion of Rice and Tracey is applied.

The calibration of the RTCL fracture criterion is conducted through the critical strain ε_0, which is determined by numerical analysis of tensile tests. Since numerical fracture strains depend on the element length an adjustment of the critical strain is necessary. Alsos et al. (2009) developed for the adjustment the relationship

$$\varepsilon_0 = n + (\varepsilon_n - n)\frac{t}{l_e}\,. \tag{3}$$

The critical strain is calculated by the exponent of the power law n, which is equal to the uniform strain and by the necking strain weighted by the ratio of plate thickness to element length t/l_e. The value ε_n correlates with the numerical fracture strain of a uniaxial tensile test discretized by shell elements with a ratio of $t/l_e = 1$. A critical strain ε_0 can be determined for any desired element length with equation (3) and a known ε_n.

5. Numerical investigations of the collision experiment considering weld joints

Alsos et al. (2009) performed large-scale experiments with stiffened plates to investigate the fracture mechanism of an outer shell of a ship during a grounding scenario. A nearly rigid body penetrates the large-scale specimen, which consists of the outer shell and bulb profiles. To reproduce the strain concentration at the fillet welds between outer shell and bulb profiles in finite element simulations Alsos et al. (2009) modeled the weld joints by shell elements with a fictitious thickness $t^* = t + 2$ mm (Fig. 3a). Since the double hull structure investigated in the present article has leg length and plate thicknesses in the same order of magnitude as the large-scale specimens of Alsos et al. (2009), this equivalent model was adopted and applied to selected weld joints (Fig. 3b). Besides the fictitious thickness the material behavior of the weld metal is applied to the weld elements and fracture is detected by the RTCL fracture criterion. The calibration of the fracture criterion is performed in the same manner as for the base material.

The numerical investigations have been performed with the explicit finite element software LS-Dyna. A constant velocity of 10 m/s has been used to minimize the simulation duration. The large-scale specimen is discretized with Belytschko-Tsay shell elements and an element length of approximately 8 mm.

The force-displacement curve of the finite element analysis reproduces the curve of the experiment well (Fig. 2a). At the fracture of the outer shell the predicted reaction force in the finite element simulation is greater than the reaction force in the experiment. The maximum reaction force at the failure of the bulb profiles of both force-displacement curves differ only slightly but the displacement in the numerically determined curve is obviously less than in the experiment. The force-displacement curves correlate well at displacements greater than 800 mm especially at the failure of the inner shell.

The deformation states of the finite element simulation at displacements of 300 mm, 600 mm and 1200 mm of the bulbous bow are shown in Fig. 4. At a displacement of 300 mm the crack path next to the weld joint of the bulb profile can be observed in the outer shell (Fig. 4a). At a displacement of 600 mm the failing of the bulb profiles is visible (Fig. 4b) which is related to a decline of the reaction force in the force-displacement curve (Fig. 2a). A fragment of outer shell, bulb profiles and PVPS is emerging and is pushed in front of the bulbous bow into the double hull structure equally to the experiment (Fig. 4c).

6. Conclusion

The experimental and numerical results of a collision experiment with an alternative stiffening system are presented. The failure mechanism and the force-displacement curve of the finite element simulation are in good correlation with the experiment. For the presented approach of validation with implemented weld joints it is

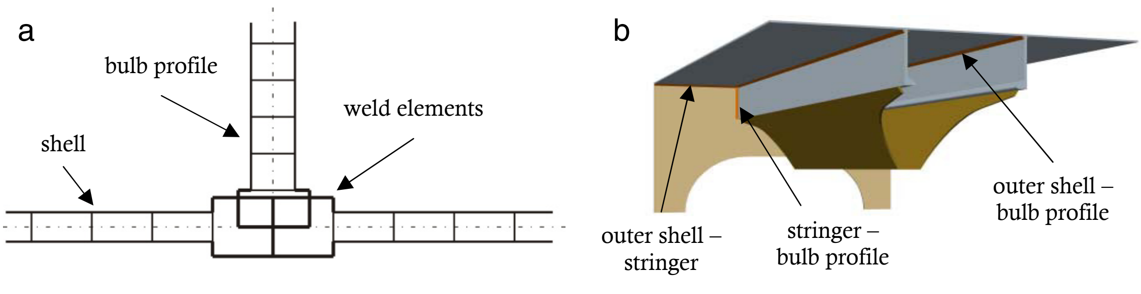

Fig. 3. (a) Schematic illustration of the equivalent model consisting of shell elements for fillet welds; (b) selected weld joints of the double hull structure.

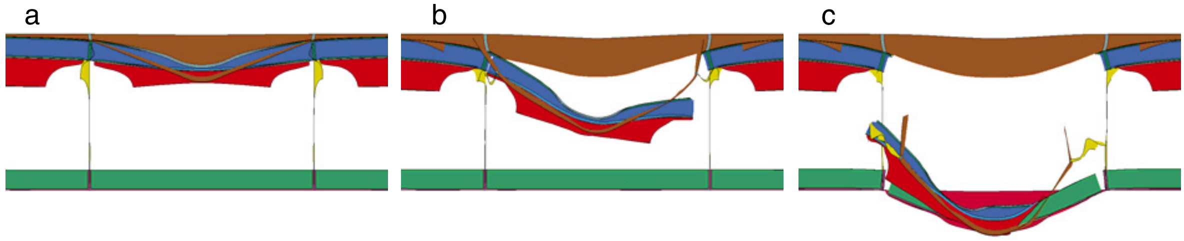

Fig. 4. Deformation states at a displacement of (a) 300 mm; (b) 600 mm; (c) 1200 mm.

necessary to carry out tensile tests of the base metal as well as of the weld metal to determine true stress-strain relations and to calibrate the RTCL fracture criterion. Furthermore, a relatively fine discretization of the large-scale specimen is crucial to consider weld joints in the finite element model. Compared with an actual double hull structure the large-scale specimen is manufactured in a reduced scale, however it is not possible to produce weld joints in the same reduced scale. Therefore, it is to assume that the influence of weld joints to the failure mechanism of the large-scale specimen is more significant than it would be in an actual double hull structure of a ship.

The modelling of weld joints with an equivalent model is to be improved and developed further in additional investigations. The weld joints consist of weld metal, base metal and the heat affected zone, but the applied equivalent model is characterized by the material behavior of the weld metal. It is to verify if a global material behavior in terms of an averaged true stress relation can be defined for the equivalent model.

Acknowledgements

The project SideColl has been accomplished in collaboration with Fraunhofer AGP, Germanischer Lloyd, Neptun Ship Design, P+S-Werften and Hamburg University of Technology. The project has been funded by the German Federal Ministry of Economy and Technology (BMWi) under the project number 03SX 309A.

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